PROJECT FINAL REPORT

Final publishable summary report

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1. Executive summary

The goal of project LOWFLIP was the development of low-cost and automated production processes for CFRP parts, which can be used for different industrial sectors. 10 partners from 5 European countries worked together from October 2013 until October 2016 to realize technologies, which are capable of being introduced in an industrial environment at the end of the project.

3 representative demonstrator parts were identified from the end users in the project: An aeronautical tail cone section by AERNNOVA, an automotive sandwich panel by CARBURES and a truck front wall by KÖGEL. Despite the different requirements from each industrial sector, a compromise solution for a newly developed material system by SGL could be found. The material offers a unique combination of out-of-autoclave processing at moderate temperatures, a high glass transition temperature, excellent mechanical properties and fast curing capabilities.

Innovative tooling concepts to achieve a fast curing cycle were developed and produced, such as 3D-membranes with integrated resistive heating, a composite tooling with an embedded heating circuit and a fluid-heated metallic mould with low thermal mass.

Two different processes were realized to be able to produce both small & complex parts as well as large components. For small parts, a robot-mounted pick & place unit has been developed within the project, which is able to transfer different types of materials accurately onto a mould. A combination of an elastic membrane and a 3D-membrane then drape the material into the final shape and perform the final curing, without needing additional machinery such as autoclaves or presses. In this way, a highly flexible process is given which can be easily adapted to different part geometries.

A novel ply placement approach has been developed by the consortium from scratch to realize large parts with a size of more than 1x1 m. By transferring the know-how from hand layup to an automated, industrial solution, a highly productive process could be realized, which can compete with existing industrial solutions regarding layup rate – at significantly lower investment costs.

In both cases, the project objectives could be achieved and industrial solutions were developed, which are now ready to be transferred into the industry.

2. Summary description of the project context and objectives

TODAY'S CHALLENGES

Fibre-reinforced polymer composite materials are leading candidates as component materials to improve the efficiency and sustainability of many transport modes. The advantages of **high performance composites** are numerous: **lighter weight**, optimum **strength and stiffness**, improved **fatigue life**, and **corrosion resistance**. These benefits translate into **greater weight savings** resulting in **improved performance, greater payloads, fuel savings and emissions reductions**.

The current manufacturing processes still represent **high capital investments** for SMEs which are a **major barrier** for their deployment in sectors like **the automotive, transport and aircraft industries**.

There are a number of technical issues that still need to be resolved before any significantly increased uptake of composites by the automotive sector can be expected.

OBJECTIVES

The specific scientific and technical objectives are the following:

- To develop, assess and analyse **new out-of-autoclave snap-cure prepreg materials** for fast curing and easy and low cost automated manipulation
- To develop **low cost and flexible multifunctional handling, placement and draping solutions** for both small complex parts and big structures
- To reduce **composite manufacturing process steps** by selective, fast and energy efficient tooling technologies
- To develop **simulation tools** to support the automation of the process with regards to material drapability, curing optimization and crash behaviour
- To design and produce **prototype manufacturing cells** that integrate the technologies validated at laboratory scale

LOWFLIP objective was to develop a low cost flexible and integrated composite parts manufacturing process for the needs of different transport sectors, which will require minimum investments

The quantified targets of the project are:

- A reduction of the investment costs compared to SoA processes of 50%
- A reduction of the energy consumption compared to SoA processes of 50%
- Equal productivity compared to SoA
- Equal technical performance compared to SoA

CONSORTIUM

In order to reach the targeted objectives, a strong consortiums has been set up, which consists of 2 research institutes, 3 end users, tooling and material experts, as well as partner for simulation software and an automation company, these are:

University of Stuttgart, Institute of Aircraft Design

http://www.ifb.uni-stuttgart.de

Fundacion Tecnalia Research and Innovation

http://www.tecnalia.com/en/

AERNNOVA ENGINEERING SOLUTIONS IBERICA SA

http://www.aernnova.com/en/

CARBURES EUROPE SA

http://carbures.com/

KÖGEL TRAILER GMBH & CO KG

http://www.koegel.com/de/

ALPEX TECHNOLOGIES GMBH

http://www.alpex-tec.com/de/

SGL CARBON GMBH

http://www.sglgroup.de

MECAS ESI SRO

https://www.esi-group.com/cz

FILL GESELLSCHAFT MBH

http://www.fill.co.at/

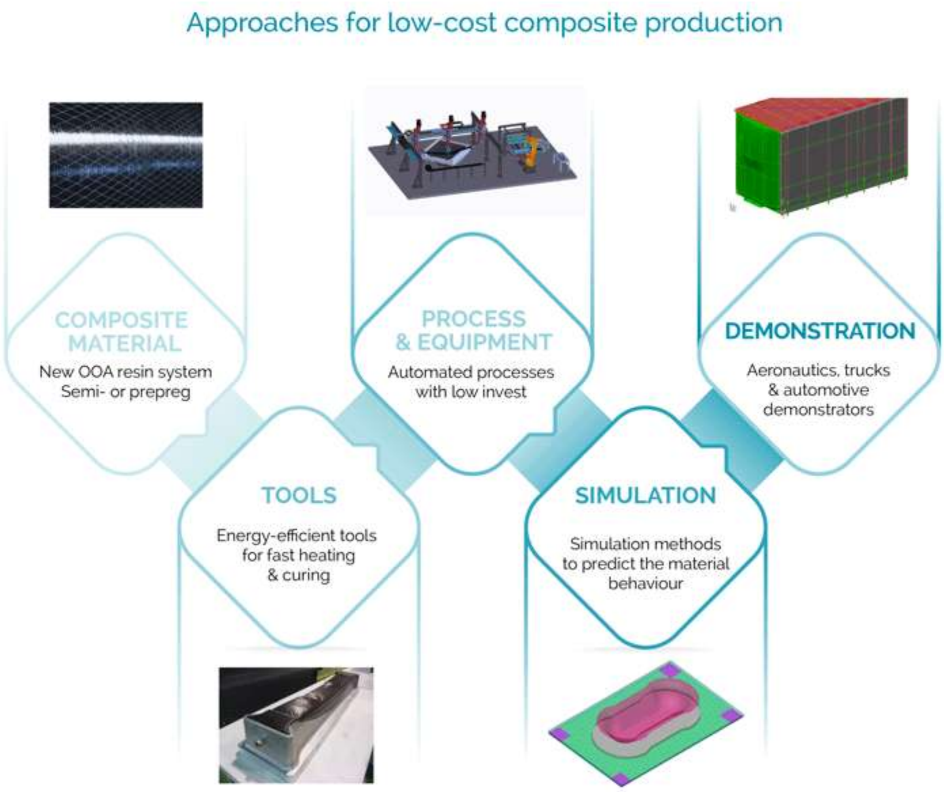
AYMING

http://www.ayming.com/

3. Description of the main S&T results/foregrounds

LOWFLIP aimed at developing new technologies in many different areas along the process chain of fiber reinforced polymers with the goal to set up automated production processes which require significantly lower invest than comparable state-of-the-art technologies. Starting with a new resin system featuring out-of-autoclave snap-cure properties with heavy-tow carbon fibers, innovative tooling concepts with fast heating and low energy-consumption were developed together with new process approaches for the automated production of cfrp parts. All developments have been accompanied by simulation methods, which served as "virtual support" during the development and application of the technologies. The developments were finally integrated into full-scale production cells, which demonstrated their capability on the example of 3 demonstrator parts from the automotive, truck and aeronautic sector.

The following chapter describes the main results of the different technological developments of LOWFLIP.



3.1. Demonstrator parts

The first task was the selection of representative demonstrator parts of the different transport sectors. In case of the automotive branch, a cross-beam structure has been identified by the partner Carbures, which has to withstand bending and torsion loads. It has a length of about 1.2m and consists of a sandwich structure with cfrp skins and a milled foam core. The parts complex shape in combination with its sandwich layup requires a highly flexible production process. The targeted volume of production has been defined as 10,000 parts per year, which results in a required curing cycle of about 30 mins.

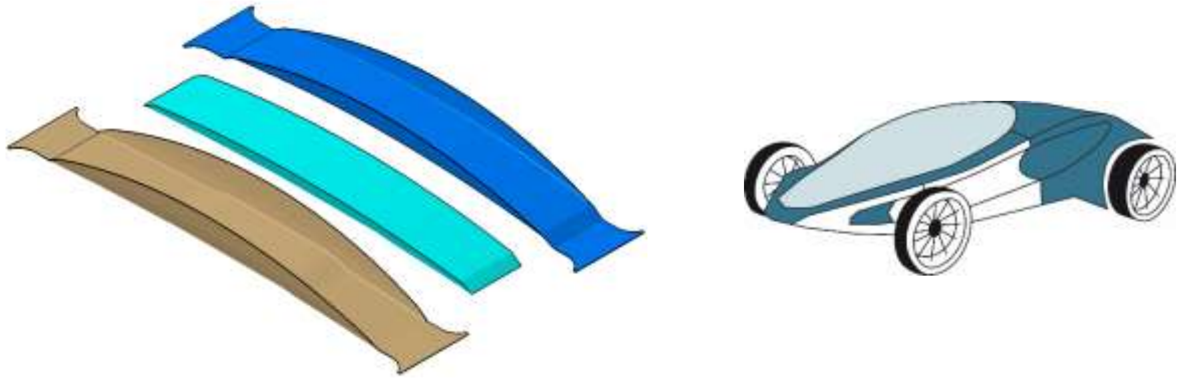


Figure 1. Automotive demonstrator by Carbures – cross-beam

The truck demonstrator is the largest of all three demonstrators. With a size of 2.5x2.9m, it required a novel automated production process with large tapes to meet the requirements of the project. The selected front wall shields the driver's cabin from the trailer and has to prevent the carried load from penetrating through. Thus it is a safety related part and has to fulfil the DIN standard EN 12642-XL, which requires a maximum load of 13.500 kN on the front wall. Geometrically, it features strongly double-curved areas, which were slightly changed from the original part to obtain a suitable design for cfrp materials. Moreover, the design flexibility arousing from the use of textile materials allowed for an aerodynamic design, which can potentially reduce the drag and thus CO2 emission during the life cycle of a truck.

Figure 2. Truck demonstrator by Kögel – front wall

The third demonstrator from the aeronautic sector is a typical stiffened skin panel from a tail cone section. The double-curved skin is stiffened with T-stringers, which have to be preshaped in a separate forming step and joined with the skin by co-curing both elements.

Here, the research activites not only focused on the production process, but also on the material quality and its damage tolerance, requiring additional ice-shedding impact tests on a comparable structure.

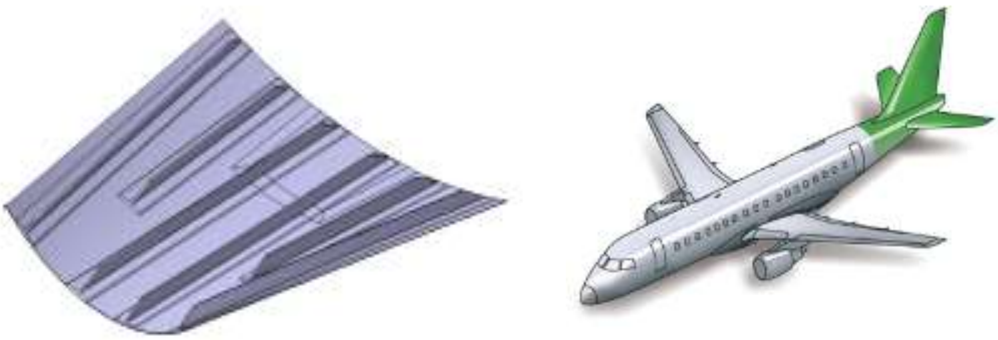


Figure 3. Aeronautical demonstrator by Aernnova – tail cone section

During the first stage of the project, the requirements on both the material and the processes to be developed were defined on the basis of these three demonstrator parts. It is obvious, that each industrial sector has different needs, which are difficult to meet in just one material or one process. Therefore, it has been tried to find common ground and to define the requirements as a compromise between different applications, which can be seen in Table 1.

3.2. New prepreg materials

The highly efficient processes and demanding applications planned in the LOWFLIP project required the development of novel prepreg materials featuring a unique combination of properties, such as:

- "Snap-cure" type curing behaviour: fast curing at elevated temperatures in combination with a high thermolatency
- Tailored tack and viscosity profile of the resin to enable the application of automated handling and out-of-autoclave curing processes
- Long shelf-life and reliable processing at room temperature
- High glass transition temperature (in the range of the curing temperature) and mechanical performance

A selection of the specific development goals that were derived from these general demands and the input collected from the project partners at the beginning of LOWFLIP is listed in Table 1.

Table 1. Goals for the development of the novel prepreg materials

Property	Value
Cure time	≤ 15 min
Cure temperature	120 °C
Applicable heating rate	≥ 10 °C/min
Curing process	Out-of-autoclave
Post-cure	No
Glass transition temperature	≥ 120 °C
Shelf-life at room temperature	≥ 21 d
Shelf-life at -18 °C	≥ 6 months
Tack at room temperature	Low

Resin type	Epoxy
Fiber type	Heavy tow industrial carbon fiber (50k)
Textile	Unidirectional and biaxial (±45°) non-crimp fabric
Fiber areal weight	≥ 300 g/m²
Impregnation level	Full / semi

Curing behaviour, storage stability, glass transition temperature and other important properties of prepreg materials are determined by the employed matrix system. For this reason, the development of a tailored resin formulation for the novel prepreg materials was a crucial point. As a first step, a suitable combination of curing agent and accelerator showing the desired snap-cure type curing behavior was identified in an extensive screening study. In a second step of the development, the base resin mixture of the formulation was optimized with regard to viscosity profile, tack properties and glass transition temperature.

An impregnation process adapted to the properties of the resin system was evaluated and optimized on a prepreg pilot line. After several iteration loops, which considered feedback from the project partners, a snap-cure epoxy resin system ("SCE79") was finalized that is able to fulfil all targets of the LOWFLIP project.

The viscosity profiles determined by rheological measurements of resin system SCE79 are shown in Figure 4.

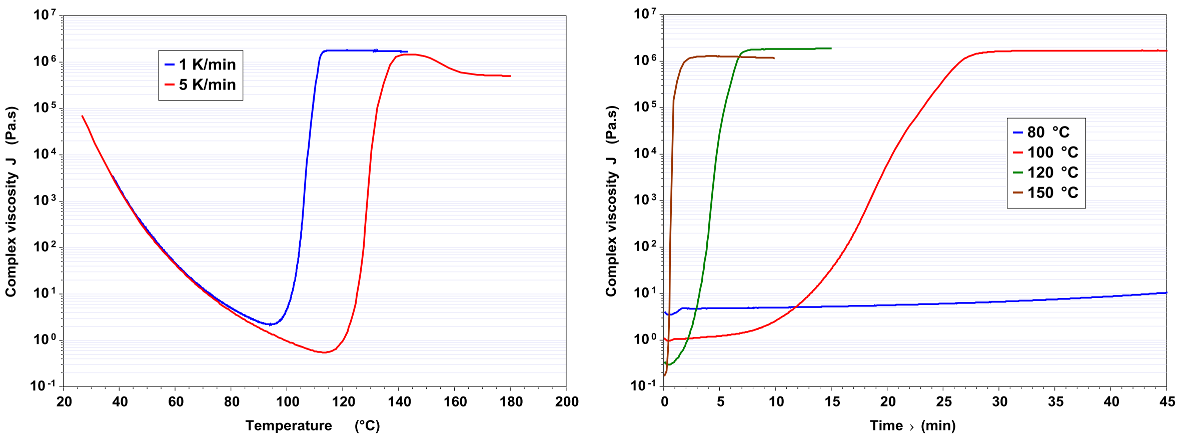


Figure 4. Dynamic (left) and isothermal (right) viscosity profiles of the developed snap-cure resin system SCE79

The dynamic profiles show a very high viscosity at room temperature indicating a solid-like behavior of the resin which results in the desired low tack of prepregs based on this resin system. The viscosity decreases rapidly with increasing temperature and low minimum viscosity values are observed which allow for a high resin flow in out-of-autoclave curing processes without the need to apply high pressure.

The isothermal viscosity profiles demonstrate the high curing performance at elevated temperatures and the excellent thermolatency of the developed resin system. While there is only a slight increase of viscosity measured at 80 °C within 45 min, rapid viscosity increases are observed at temperatures of 100 °C and higher. A stable viscosity niveau, indicating a largely completed curing reaction, is for example reached in less than

10 min at 120 °C. At 150 °C it takes around 3 min to reach a plateau, showing the potential for even shorter curing cycles if higher curing temperatures may be chosen.

The remarkable curing performance and latency of the new resin system SCE79 is also illustrated in the time/conversion plots compiled by Tecnalia via kinetic modelling (Figure 5). At temperatures ≥ 120 °C high degrees of conversion (> 90 %) can be obtained within minutes. At 80 °C a pre-compaction step can be performed for at least 20 min during the laminate production without starting the curing reaction.

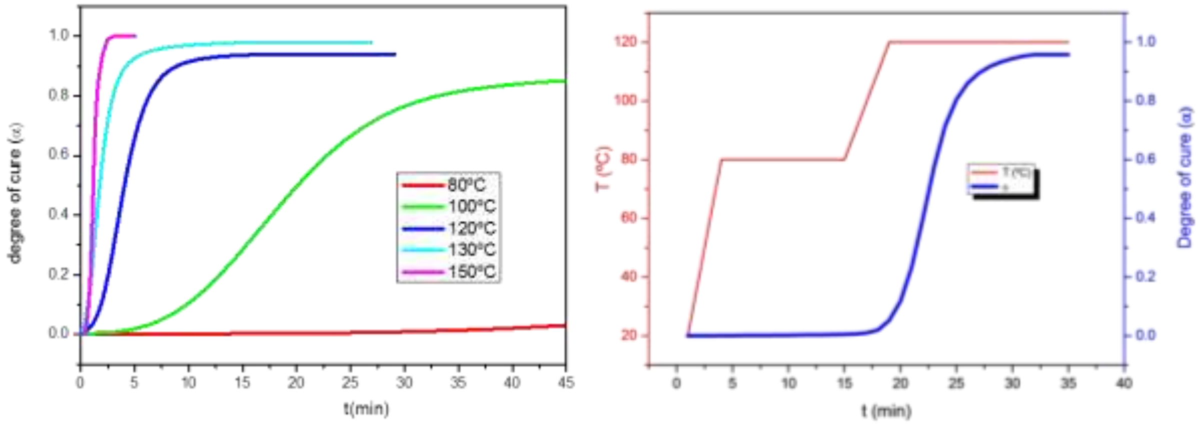


Figure 5. Time/conversion plots for resin SCE79 (left: isothermal at different temperatures; right: curing cycle with pre-compaction step at 80 °C)

The newly developed resin system was used to prepare prepreg trial materials based on 50k carbon fibers. Different textiles and impregnation levels were employed and evaluated together with project partners Tecnalia and IFB regarding prototype part design, capability for automated processing, drapability and laminate quality.

One selected material is based on a biaxial ±45° non-crimp fabric (fiber areal weight 400 g/m²) that was asymmetrically impregnated ("semi-preg") to provide best processability in pick & place handling. The other selected material is a unidirectional (UD) fully impregnated prepreg with a fiber areal weight of 300 g/m² and without fixation by a scrim-bonding or stitching yarn. The tack of the obtained UD prepreg is on the one hand sufficiently low to allow for an easy processing in tape laying processes, but on the other hand high enough to provide sufficient adhesion between stacked layers. Furthermore, the ductility of the prepreg has been maintained.

The prepared prepreg materials were also characterized regarding their curing performance and mechanical properties together with Tecnalia and IFB. Figure 6 shows a comparison of the DSC curves of the neat resin SCE79 and a prepreg based on SCE79 (left). Also, the dynamic mechanical analysis of a laminate prepared from the UD prepreg that was cured for 15 min at 120 °C is shown (right).

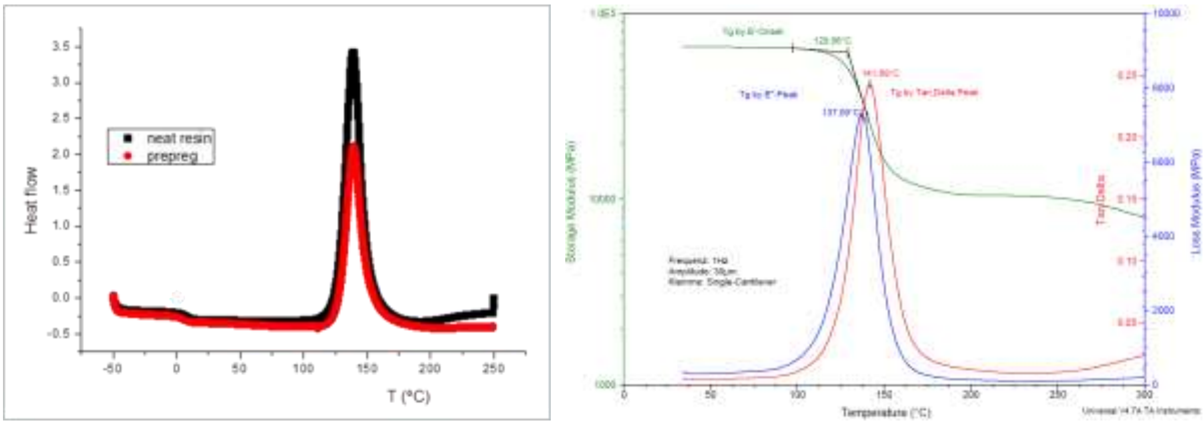


Figure 6. DSC of a prepreg compared to the neat resin SCE79 (left) and DMA of a unidirectional laminate of the prepreg (right) (curing cycle: 15 min at 120 °C)

The reaction peak observed in the DSC exhibits the same characteristics (e.g. onset and peak temperature) for the neat resin and the corresponding prepreg which indicates that the excellent curing behaviour of the resin is retained also in combination with the carbon fibers. The DMA shows a well-defined glass transition at a temperature between 120 - 130 °C (E'-onset) which is above curing temperature. This allows for a hot demoulding of cured composite parts.

Despite the high curing performance at elevated temperatures a long shelf-life of at least 4 weeks at room temperature was obtained for the resin and prepregs based on it (determined by viscosity and DSC measurements).

The results of mechanical testing of the UD prepreg are shown in Table 2. Two different curing methods were used in order to investigate their influence on the mechanical properties and to assess the mechanical potential of the developed material system. The first method was a vacuum-assisted process (vacuum bag curing in an oven) and the second one was a standard hot press process applying a pressure of 5 bar. A pre-compaction step at 80 °C prior to curing at 120 °C was conducted in both methods.

Table 2. Mechanical properties of unidirectional laminates prepared under different conditions (curing cycle in both cases: 10 min at 80 °C + 15 min at 120 °C)

Property	Standard	Values obtained with UD prepreg (SCE79, 50k CF, FAW 300 g/m²)	
		Vacuum bag (30 mbar vac.)	Compression molding (5 bar)
Fiber volume content [%]	EN 2564	56.7 (± 0.9)	62.4 (± 2.3)
0° Tensile strength [MPa]	EN 2561	1737 (± 54)	1872 (± 43)
0° Tensile modulus [GPa]	EN 2561	129.8 (± 8.5)	133.1 (± 2.0)
90° Tensile strength [MPa]	ISO 527-5	36.9 (± 7.8)	56.2 (± 5.7)
90° Tensile modulus [GPa]	ISO 527-5	7.9 (± 0.3)	8.8 (± 0.2)
0° Compressive strength [MPa]	ISO 14126	1133 (± 117)	1282 (± 80)
0° Compressive modulus [GPa]	ISO 14126	118.2 (± 3.8)	123.0 (± 3.0)
Interlaminar shear strength [MPa]	EN 2563	70.1 (± 1.6)	83.2 (± 3.2)
0° Flexural strength [MPa]	ISO 14125B	1300 (± 34)	1388 (± 13)

0° Flexural modulus [GPa]	ISO 14125B	108.0 (± 4.8)	105.5 (± 2.5)
90° Flexural strength [MPa]	ISO 14125B	60.5 (± 4.8)	74.9 (± 2.9)
90° Flexural modulus [GPa]	ISO 14125B	6.9 (± 0.3)	8.5 (± 0.2)
In-plane shear strength [MPa]	ISO 14129	56.6 (± 0.6)	not tested
In-plane shear modulus [GPa]	ISO 14129	3.9 (± 0.1)	not tested

It can be seen that the press process at 5 bar generally leads to higher mechanical properties which can be explained by a higher fiber volume content and higher laminate quality, both resulting from the increased pressure level compared with the vacuum-assisted curing process. The values obtained with the vacuum bag setup are nevertheless on a satisfactory level, especially if considering the short curing cycle and rather simple process.

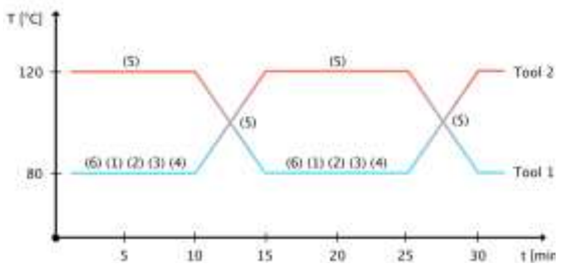
In conclusion, prepreg materials based on 50k carbon fibers and a novel snap-cure epoxy resin system ("SCE79") were developed by SGL according to the demands of the LOWFLIP project. These materials feature a fast cure at elevated temperatures (e.g. 15 min at 120 °C), a high glass transition temperature of 125 °C, long shelf-life at room temperature (≥ 4 weeks) and competitive mechanical properties. The new prepregs were further adjusted to automated handling processes and out-of-autoclave curing of large composite parts. Compared to standard prepreg materials cured in traditional autoclave processes, significant reductions of cycle times, energy consumption and investment costs can be achieved.

3.3. Tools for fast & energy-efficient heating

In order to meet the demands of an energy-efficient process, new innovative tooling concepts were investigated within LOWFLIP which should provide mainly two features: Low energy-consumption and fast heating capabilities. State-of-the-art tooling are typically a metallic solution milled out of block materials such as aluminium or invar steel with high thermal masses. Therefore, different concepts were investigated by the partners.

Automotive

The design of the automotive tooling aims to manufacture 10000 + pieces per year. To do so the developed process aims to use two tools, which rotate between a preparation and a curing phase.



1. Draping of the bottom skin onto the tool
2. Forming of the bottom sin with a heated membrane
3. Positioning of the core
4. Draping the top skin
5. Finalizing the form and the curing
6. Cooling and demolding

The tool has to provide fast heating and cooling ramps as they are key issues for the process. To ensure fast heating and cooling the tool has to be a low mass solution, which is still capable of withstanding of the occurring forces.

The solution is an aluminum tool with a sophisticated design for the heating circuit. The rips inside the tool provide a larger surface to increase energy exchange between the tool and the medium. They also cause a turbulent flow, which increases the energy exchange as well. A suitable heating/cooling device is very important to use the tools benefits.

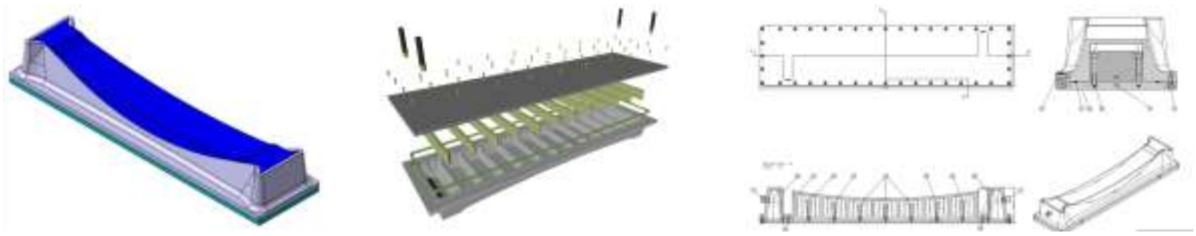


Figure 7. Automotive tool design

Figure 8. Final tool (heating test and with part) and heating ramp

The tool was manufactured and the heating ramp was tested. The results were very promising and showed the property to heat up very fast. The drop down in the graph derives from the refilling of the heating device with cold water to compensate the volume of the tool. For the production process the heat transfer between the two tools will be optimized and the drop down is not relevant any more.

The final process was changed and the forming of the bottom skin is not performed any more, which saves time and allows an even faster production cycle.

Transportation

The transportation industries need fewer parts than the automotive sector, but the parts are much larger. The demonstrator for transportation is very large with a size of about

3 m x 2,5 m and has a 3-D shaped structure. The issues hereby are the tape-laying and the energy consumption for the curing.

The energy consumption of a steel tool to heat such a tool would be 179 kWh. An optimized version with 30 mm steel mould and a substructure made of steel still would require about 45 kWh; the convection of the larger surface is not included. To reduce the mass significantly the use of CFRP with embedded heating wires was focused. The designed CFRP tool needs about 4 kWh. Furthermore the heating ramp of the CFRP tool is much faster than the heating appears close to the surface. The values of the energy consumption will be higher as the calculations did not include the convection, the parts and thermal insulation.

To manufacture a CFRP tool a master tool is needed, which is made of plastics or sometimes timber. The GFRP is laminated on the master tool, which means all properties of the GFRP tool have to be part of the master tool.

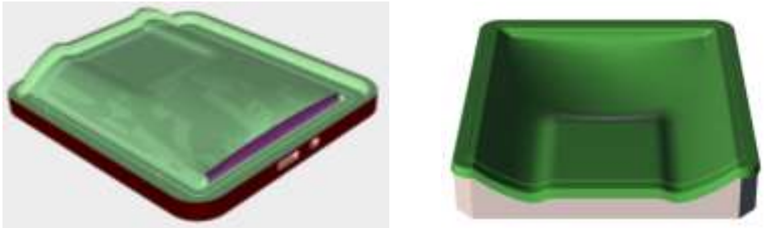


Figure 9: Master tool and CFRP tool

Figure 10. Manufactured master tool and final CFRP tool

The master tool was made of medium density fiber board and varnished to provide a vacuum tight surface for manufacturing the CRFP tool. The CRFP tool has embedded heating wires and a honeycomb structure underneath to ensure a high stability for the tape laying process.

Aeronautics

The aviation industry has very complex shaped parts that often have integrated parts, like stringers. Therefore the production is based on manual work and only can provide expensive parts at small quantities. The performing is usually made inside the metal curing tools, which takes them out of the production process whilst curing. The production uses autoclaves to cure the parts, which are run with variotherm heating ramps. The energy consumption is enormous.

The idea to improve the manufacturing for the aviation industry is to separate the preforming and the curing. The preform tool is made of an economic material and available in large quantities. A membrane is added to the preform tool to manufacture the preform. To cure the part a heatable metal tool is used, which remains at the curing temperature. As the preforms are quite soft and easy to damage the transfer of the preform will be done with the membrane. The curing tools are attached to preform tool and the membrane is evacuated to the metal tool. As the tools fits perfectly with each other the fibers aren't moved.

Figure 11. Preform tool, with membrane and inserts and the transferred membrane at the curing tool

Figure 12. Preform tool and curing tool

Figure 13. Silicone membrane

The membrane was partly thicker than expected, which led to wrinkles. With some adjustments to the tool the process is still usable.

3.4. Development of innovative, low-cost and automated manufacturing technologies

Due to the different requirements on part geometry between the automotive and truck/aeronautic sector, two different manufacturing approaches had to be defined to be able to realize the demonstrator parts with an automated process.

In case of the small and complex geometries addressed by the automotive demonstrator, a pick & place approach combined with an elastic membrane was developed.

For large parts with lower curvature such as the truck front wall and the tail cone section, a novel tapelaying process has been designed from scratch.

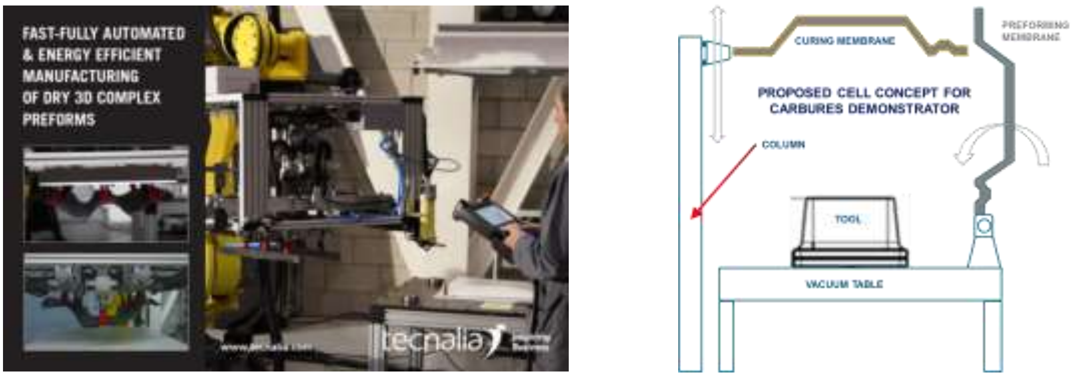


Figure 14. Tecnacomp baseline process (left) and LOWFLIP concept for small & complex parts

As it is shown in Figure 14, the approach for small & complex parts consists of a pick & place unit mounted on a robot, which has originally been developed by Tecnalia. The pick & place device should then be combined with a newly developed membrane draping approach, which consists of two different types of membrane material: A highly elastic membrane in order to drape the material on the complex mould and a 3D-membrane with integrated resistive heating circuits that is later heated up to cure the part. In this way, an automated process chain is given that can be applied to varying geometries and materials.

In order to find suitable solutions for the membranes, durability tests were performed. The results showed that the right membrane material is crucial to obtain a robust process, especially as epoxy based resin systems can significantly reduce the membrane properties after several curing cycles. By analysing membranes mechanically, a material with a good combination of flexibility and robustness was found.

Moreover, pick & place tests were performed on a lab-scale to test different grippers which are capable of transferring a stack of prepreg material from a feeding table to the mould. The lab-scale trials were validated on the automotive tool provided by the partner ALPEX and led to the design of the full-scale cell by FILL. It features a pneumatic gripper system that is mounted on a robot, which can pick up single plies or stacks from a feeding table and place them on the mould. In order to be able to deal with different types of material, different pneumatic gripper solutions are combined within one device. Moreover, the grippers are mounted on several axes, so that their position can be adjusted in order to deal with different cut geometries. It is also possible to pre-shape the stack before placing it onto the mould, so that a reproducible positioning can be achieved.

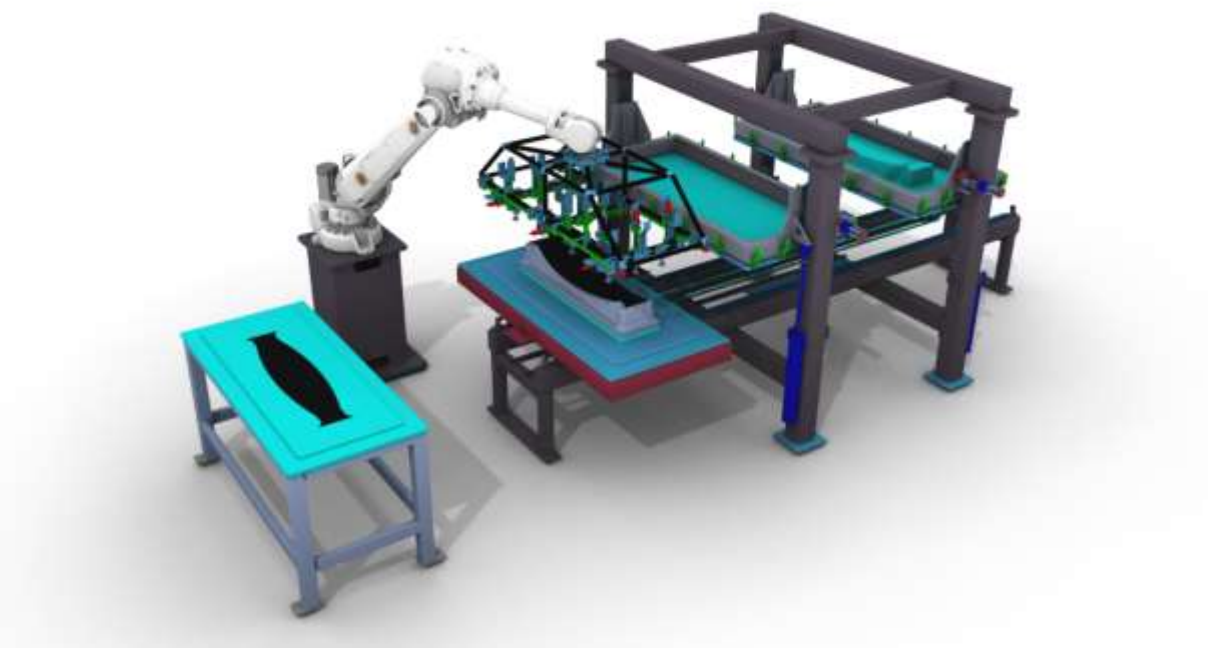


Figure 15. Full-scale production cell for small & complex parts

The full-scale cell has been evaluated on the basis of the production of several automotive demonstrator parts. A cycle time of around 20 mins can be achieved with the system if one mould is used. By using two moulds which are processed in parallel, an optimised cycle time of 10 mins is realistic. Since an overall production cycle of 30 mins has been targeted, it was shown that the combination of a fast-curing material and high productivity was successful.

For large component, a novel tapelaying approach has been developed from scratch. The basic idea is to separate the material feeding from the compaction system by designing two gripper units, which position a tape of unidirectional material over a mould and a compaction unit which then forms and consolidates the tape on the mould. Available market solutions (Automated Fibre Placement, Automated Tapelaying) typically consist of highly complex, integrated devices which are mounted on a gantry or an industrial robot. Moreover, they are mainly designed for the use with one single type of material. The

LOWFLIP process aims at reducing the complexity of integrated tapelaying devices and to be much more flexible, so that different types of fabrics can be processed.

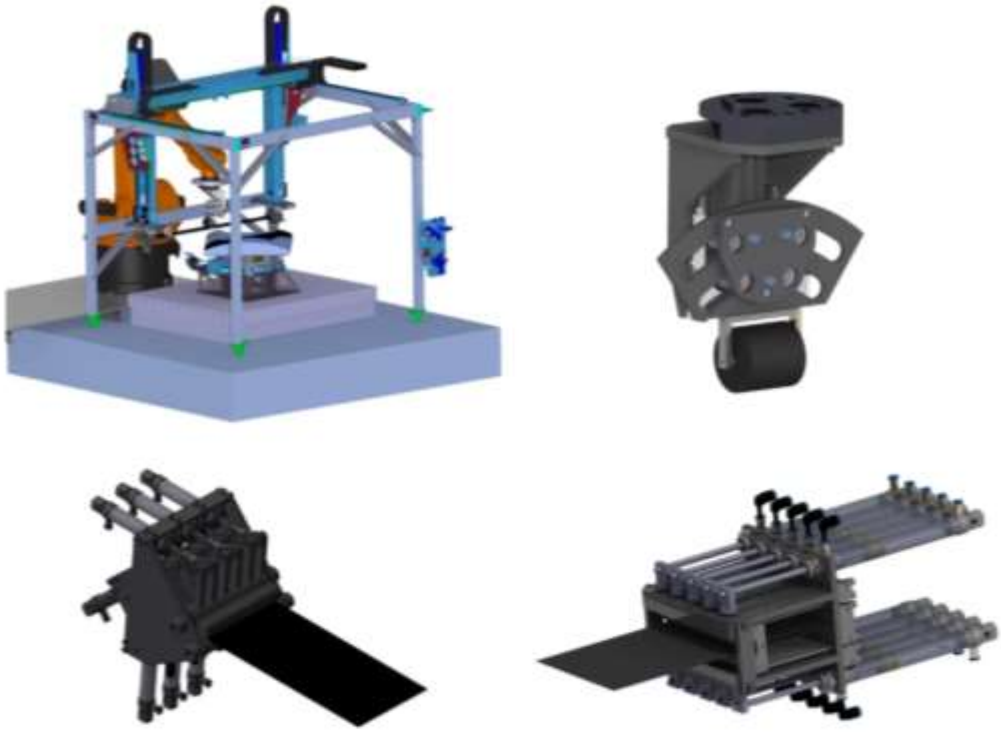


Figure 16. Lab-scale cell for the development of gripper and compaction devices

The most challenging issue was the development of suitable gripper and compaction systems, as no existing solution could be used for this novel approach. In order to have a highly productive process, tapes with a width of 300 mm or more were used. Consequently, the tapes have to be draped over double curved shapes, which leads to length deviations between the unidirectional fibers. The solution was found in the development of segmented grippers, which are able to pull out the occurring length deviations and hold the fibers straight in order to prevent wrinkles. The compaction roller, which has to be both stiff to consolidate the material and flexible in order to adapt on the complex geometry, has been another innovative development by the consortium. The final design of both subsystems is shown in Figure 17.

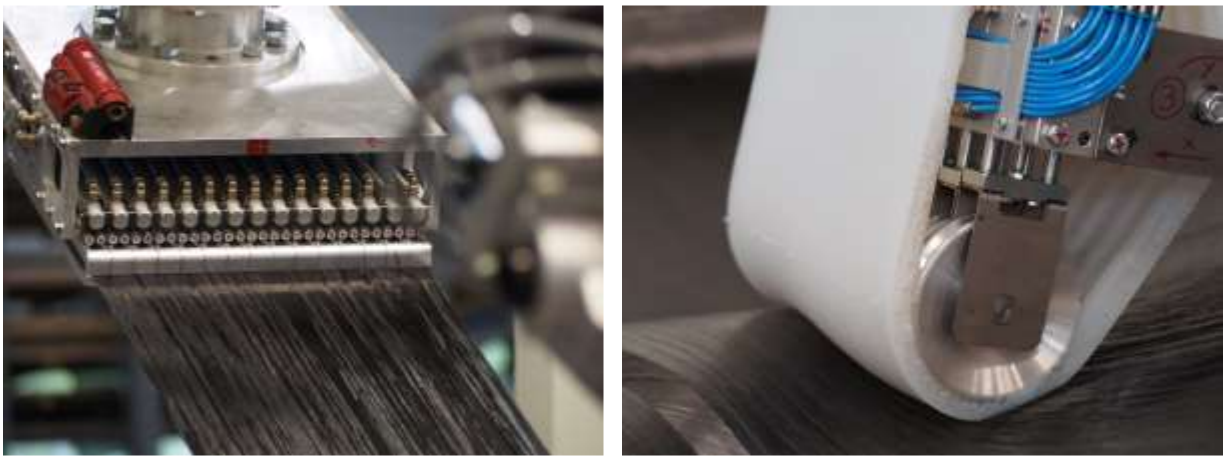


Figure 17. Segmented gripper and adaptive compaction roller system

After several iterations, the design of the final full-scale production cell for large parts was found. It consists of three industrial robots mounted on a linear axis, which are used for taking up the material from a ply cutter and then position the tape over the mould. Depending on the required fiber orientation, the tool can be rotated, so that any demanded angle can be realized. The compaction roller is mounted on the third robot, which then presses the tape on the mould. A smart off-line programming software has been a key to finally realize the demonstrator parts in this automated process.

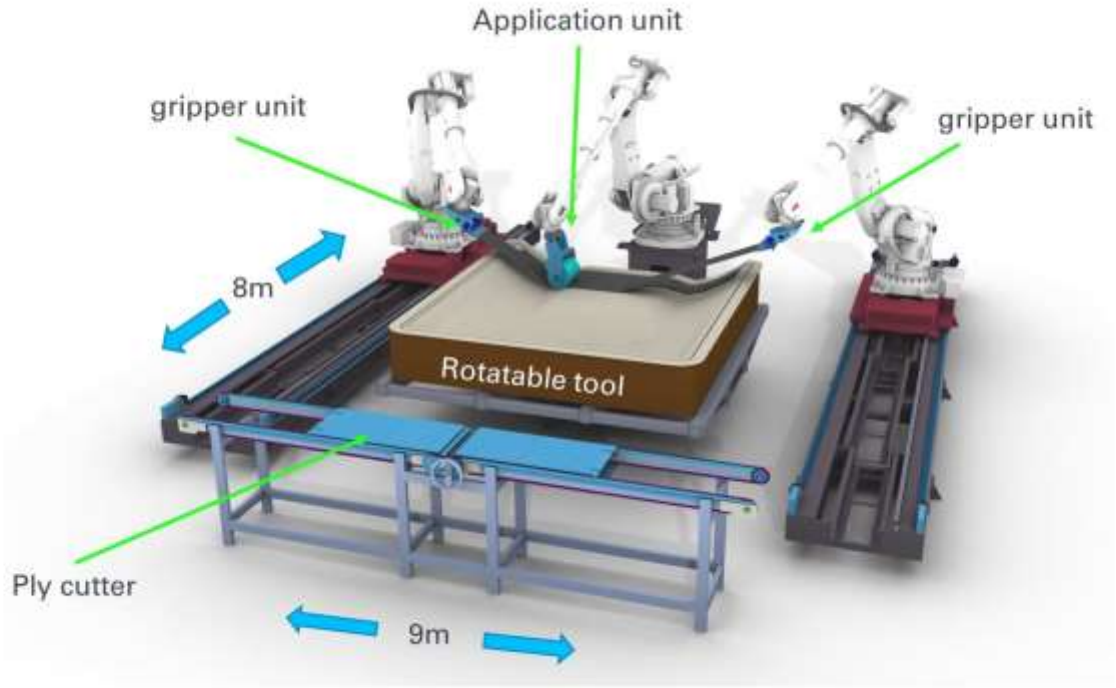


Figure 18. Full-scape production cell for large parts

The process is competitive with regards to its productivity with current AFP processes. During the production of the truck front wall, a layup rate of around 10-19 kg/hour could be achieved, depending on the complexity of the geometry. Here, a tape with 300 mm width and a fiber areal weight of 300 g/m² has been used. During the process, the mould is slightly heated up to increase the tack of the prepreg material. A curing cycle of 40 mins could be achieved with the available mould, which could further be decreased by increasing the heat-up rate of the mould. The material scrap rate was in the range of less than 10% and could be reduced to less than 5% by optimizing the robot programming and thus the tape lengths.

In summary, two innovative automated production processes have been developed by the LOWFLIP consortium, which allow for the production of complex CFRP components with high volume. Due the combination of fast out-of-autoclave curing, high flexibility with regards to part geometries and materials, as well as low investment costs, they provide a unique solution on the market for part suppliers.

3.5. Simulation tools for composite manufacturing and part design

In order to have a low cost part from composite material, apart of the direct costs of material and energy consumed during its manufacturing, it is necessary to be able to define part's design and the way how to produce it in a reasonable timeframe with as little costs as possible. It will be only possible if engineers can avoid experiments with real prototypes and determine part characteristics, manufacturability and repeatability before it comes to the production. This can be enabled by introducing virtual tools for assessment of component properties and manufacturing process feasibility.

Within the project there have been tested and also validated several simulation tools and possibilities for various aspects of manufacturing process and both static and dynamic responses of components produced from the new material with a given forming and curing cycles.

Forming behaviour of the new material has been tested on an identified simple tool, so called double dome, which is small enough for basic experiments but at the same time enables to investigate and validate several forming phenomena occurring during composite forming process due to the availability of flat areas, single curvature and double curvature areas.

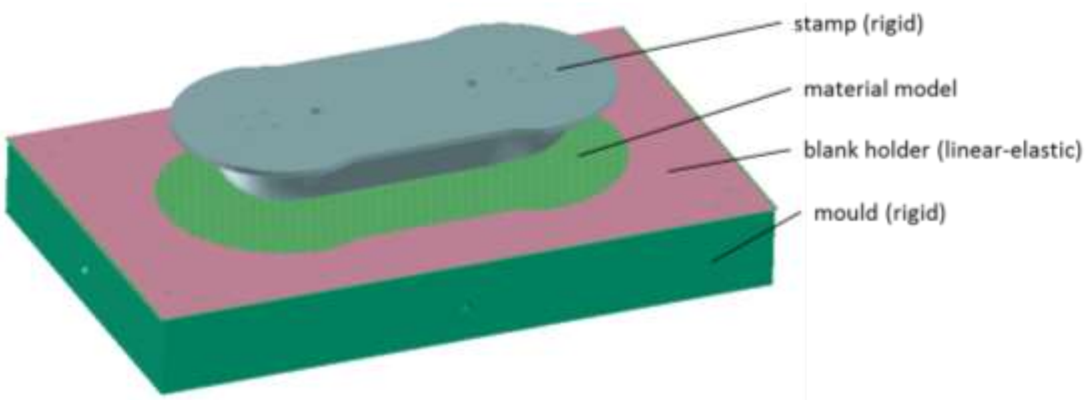


Figure 19. Mesoscopic simulation model of the draping process (top) and experimental draping test rig

With a basic characterization tests such as cantilever test, bending test and bias extension test, a material behaviour under forming conditions such as prepreg/semipreg stiffness, bending stiffness, shear modulus, has been identified and obtained material properties were used for virtual forming simulations. Two approaches have been investigated, microscopic and macroscopic, each for different type of reinforcement used.

Results of macroscopic forming simulation is compared with experimental forming. Part outlines are well corresponding as well as defects in the part, see Figure X-Y2 and Figure X-Y3

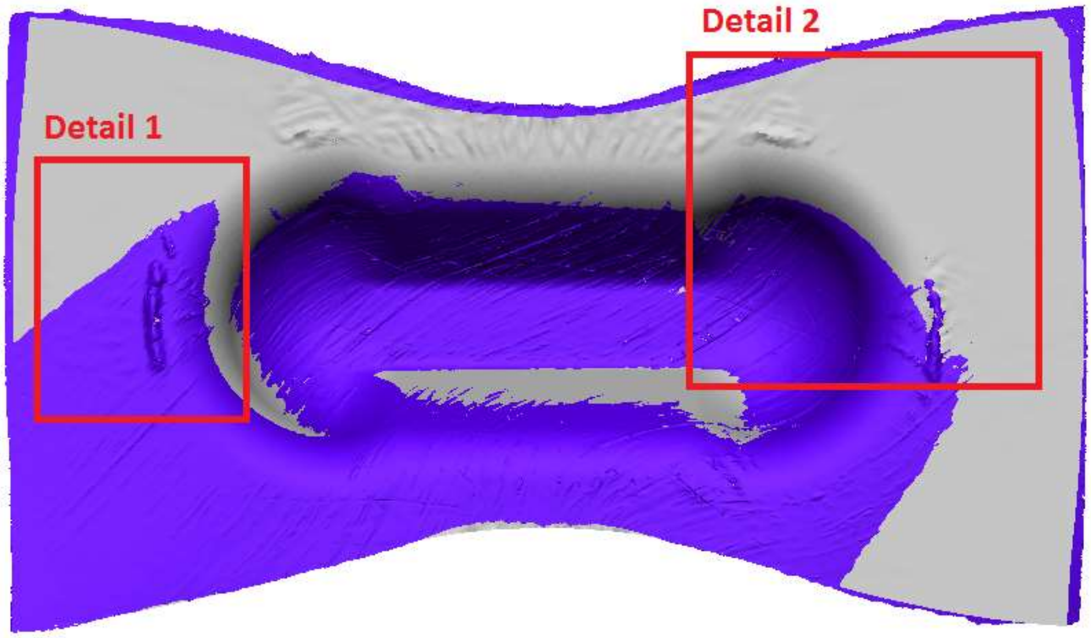


Figure 20. Macroscopic model – simulation result

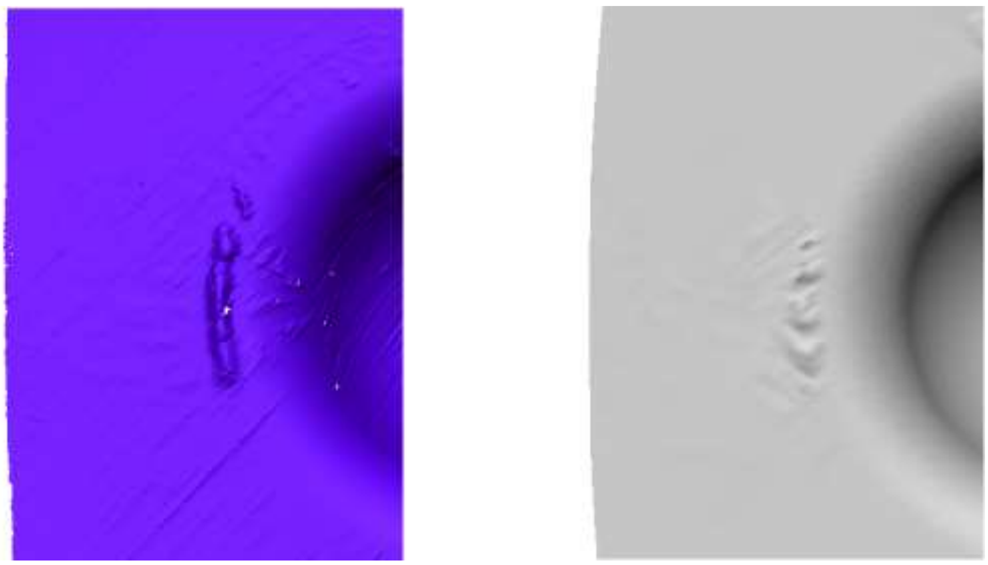


Figure 21. **Macroscopic model – detail side**

In order to precisely predict fiber architecture parameters, the use of mesoscopic material models has been investigated within WP5. Here, the yarns and matrix are represented as separate materials in the simulation model with different properties. These properties were measured experimentally with bias extension and cantilever tests at different temperatures, since the properties of the matrix material are highly temperature dependent. It could be shown that deviations from the ideal fiber architecture occur in the simulation model to the same degree as in reality, if all parameters are implemented correctly. These deviations are for example gaps or undulations, which can be seen in Figure 22.

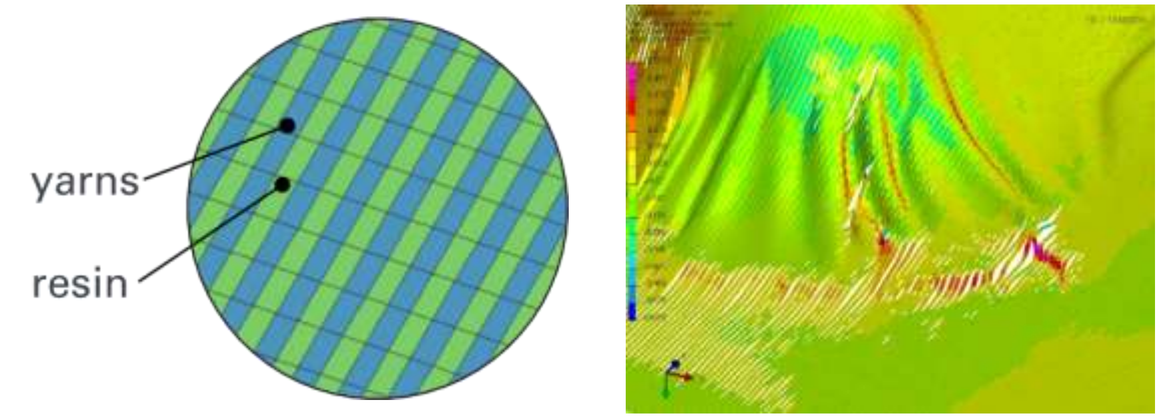


Figure 22. Mesoscopic material model and draping simulation results with occurring defects

One of the manufacturing processes within this project was an automatic tape-laying process, for which there has been build a new tool for analysing mold/part surface complexity with respect to laying procedure, such as starting point for laying, direction of laying, tape width. This tool enables the user to analyse a curvature of part or mold surface in the tape direction and orthogonal direction, Figure X-Y4, and tapes distribution on the part with differences of lengths of edges of a single tape laid on the tool, Figure X-Y5 and of course tapes themselves on the surface, Figure X-Y6.

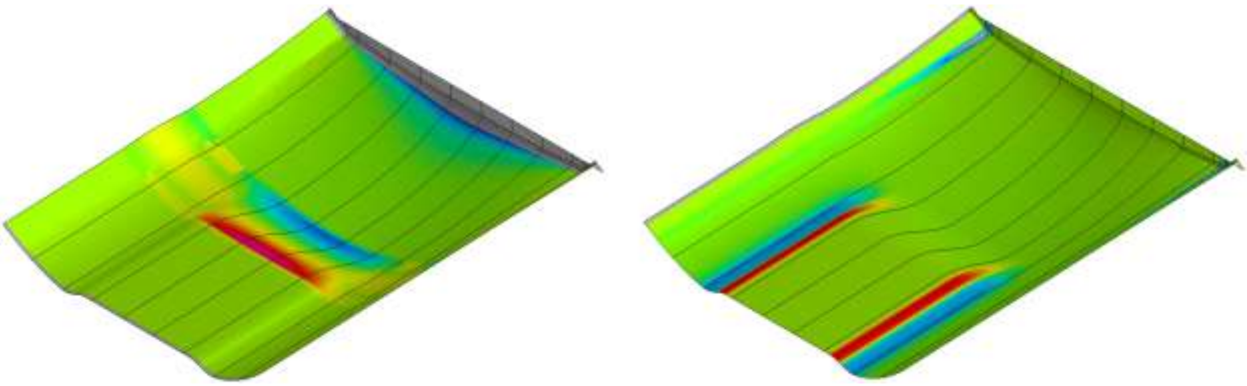


Figure X-Y4 Surface curvature in tape direction and layup direction

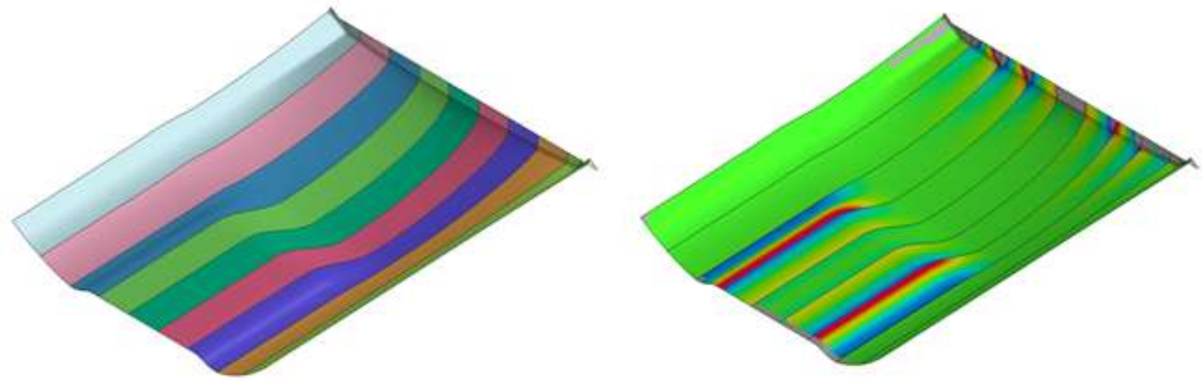


Figure X-Y5 Tapes on the part and edge lengths' differences

Virtual modeling has a significant role in components' design. There have been built several numerical models to iterate on final dimensioning of a demonstrator part – trailer front wall structure, and an optimal one found for prescribed loading states with identified material parameters. Final shape to be seen at Figure X-Y6 and thicknesses with corresponding results showing the part is within the Tsai Wu criteria and also below maximum allowed deformation Figure X-Y7.

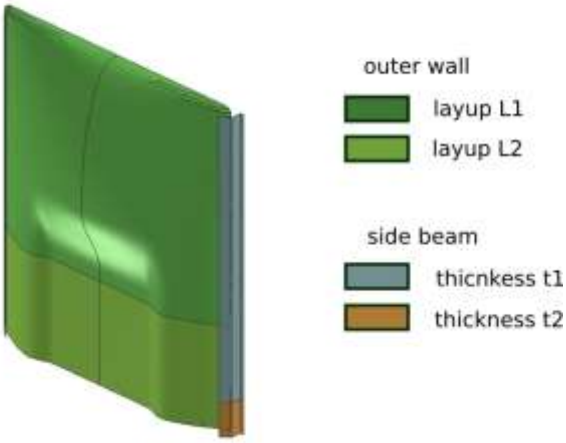


Figure X-Y6 Final design - Thickness and mass of parts

Part	Inner wall	Outer wall L1	Outer wall L2	Side beam t1	Side beam t2	Inner beam	Bottom part	Front wall substructure
Thickness [mm]	1.5	2.4	3.6	3	5	3	4	
Mass [kg]	26.8	19.7	13.3	4.6	0.9	9.8	2	**92.4**

Table Z Final design - Thickness and mass of parts

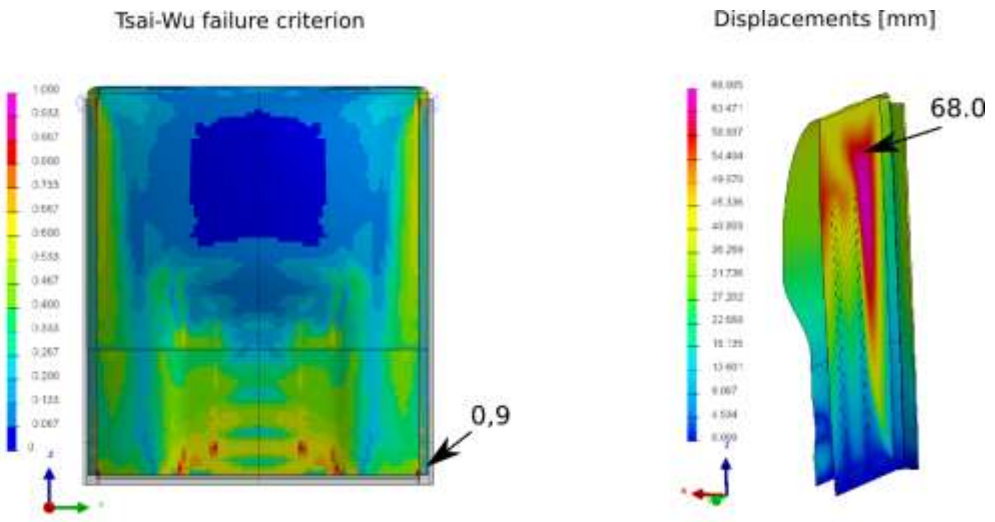


Figure X-Y7 Final design - Tsai Wu failure creterion and displacements

Another manufacturing process within the project was the CARBURES automotive demonstrator production. A prediction of the displacements with PAM-DISTORTION was performed, and correlated quite well with reality. The part had slight shrinkage during the curing and coooling. Neither internal stresses nor displacements after the curing and cooling phase and before demoulding were also very big.

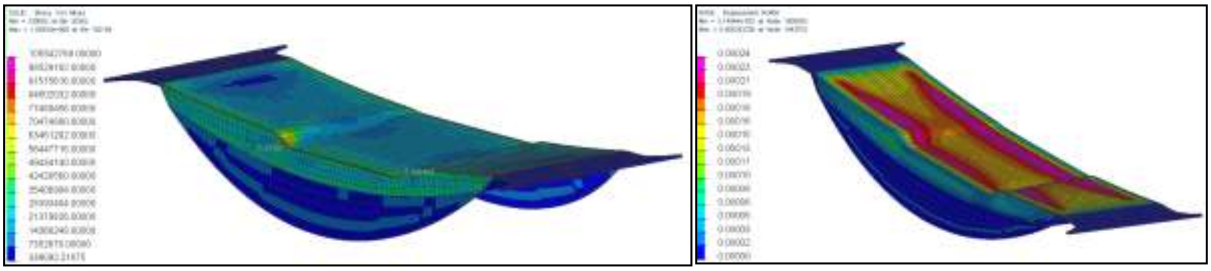


Figure 23: Stresses and displacements of automotive demonstrator after curing and before demoulding. Units in Pascals (pa) and meters (m)

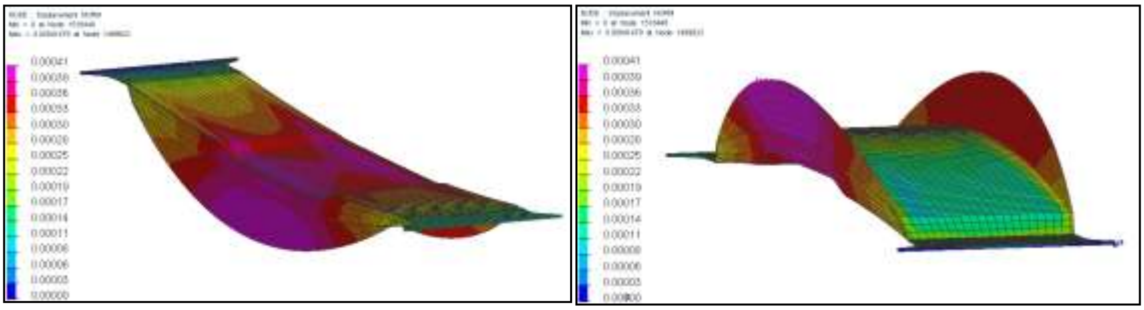


Figure 24: Distortions obtained after demoulding. Units in meters (m)

Figure 25: Distortions obtained after demoulding. Units in meters (m)

Therefore, an accurate correlation between simulation and experimental trials was carried out. Slight angular deformations and part shape displacements were measured as predicted with the model. The methodology and the software used it is therefore validated with the manufacturing trial.

Damage Tolerance behavior of the composite materials at low energy impacts is crutial to be known, due to has a great importance in sizing allowables of aeronautical structures. This material knowledge can be done by means of big test campaigns spending a lot of time in manufacturing, inspecting, cutting, testing and evaluating test results, or can be done by means of virtual testing by simulation.

There has been performed a simulation of dynamic material response on impact at different energies with a shell model, which means each layer of the laminate is represented by a layer of shell elements, see Figure 26.

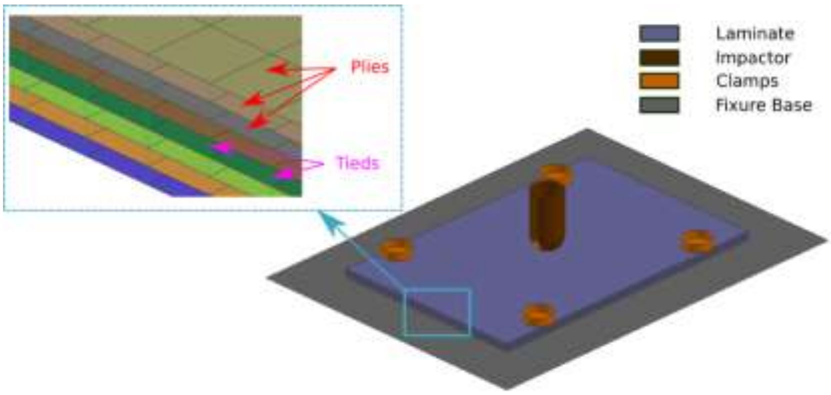


Figure 26: Model with shell elements

A Ladeveze material model in PAM-CRASH software has been used which enables an advanced possibility for modeling of non-linear behavior of laminate.

Results from simulation of impact of laminate plate have been compared to experimental tests. Comparison of force and displacement versus time is shown at Figure 27.

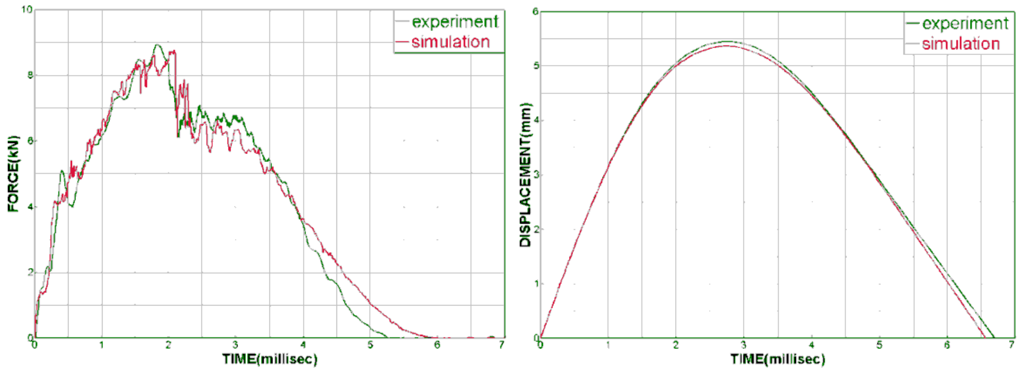


Figure 27: Comparison of time history of impactor contact force (left) and displacement (right) at 30 J

Very good correlation for energy 30J has been observed with shell model and also the other 2 scenarios (20J and 40J) gives acceptable correlation between simulation and experiment.

Dynamic explicit software solution ABAQUS was also used, and models of drop weight tower and the results were quite good also for 20J and with reasonable accuracy for 30J and 40J.

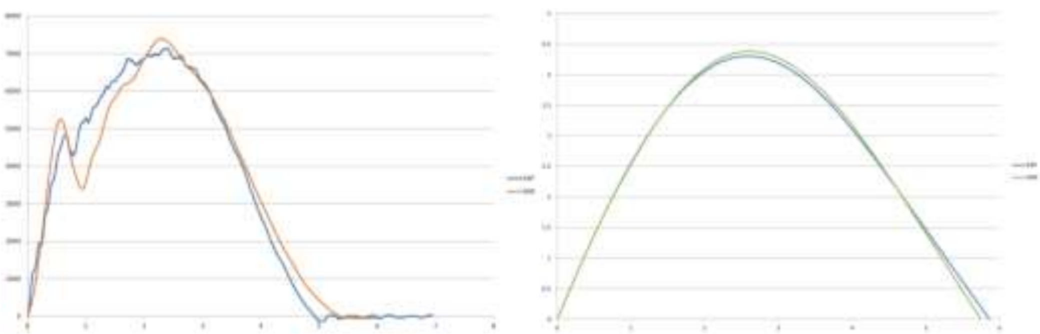


Figure 28: Comparison of time history of impactor contact force (left) and displacement (right) at 20 J

Impact scenarios like hail impact, debris impact and Ice Shedding impact over a composite fuselage are critical for knowing if the structure is able to be certified for flying. A simulation of an experimental Ice Shedding test was performed over a representative stiffened panel with the LOWFLIP material UD prepreg 300 gsm.

In next Figures it can be seen that the simulation can capture with enough accuracy not only the interlaminar failure (compared with Phased array NDT inspection), but also the intralaminar failure produced in the upper and lower surface of the curved stiffened panel. The impact was carried out at 142 m/s with an approximated energy of 1,600 J.

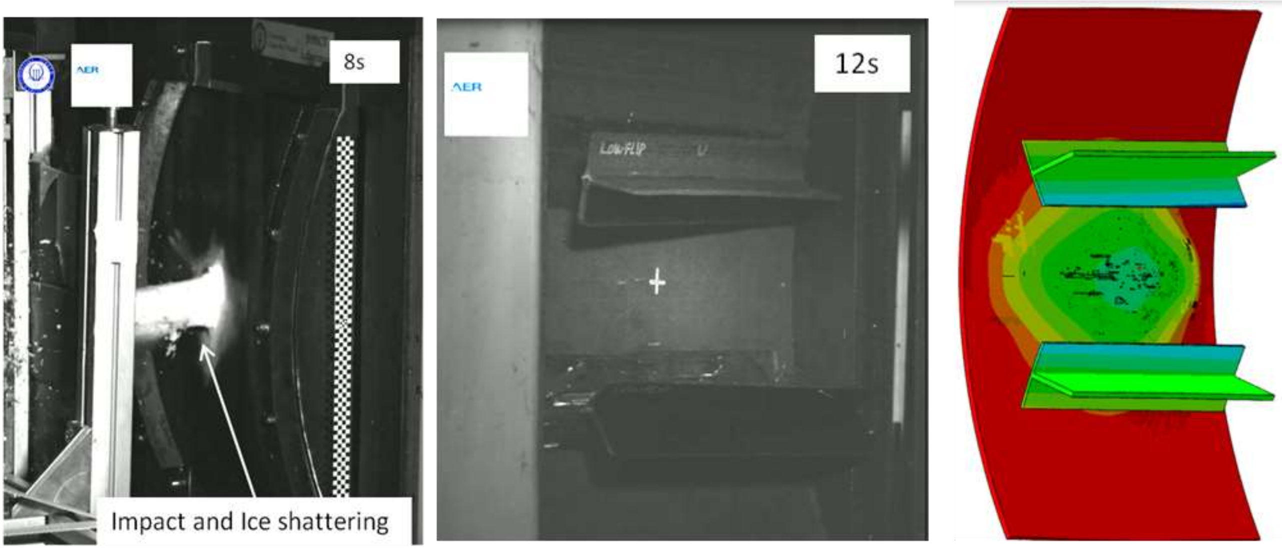


Figure 29: Correlation between experimental test (left and center) and simulation results (right) in the Ice impact Shedding

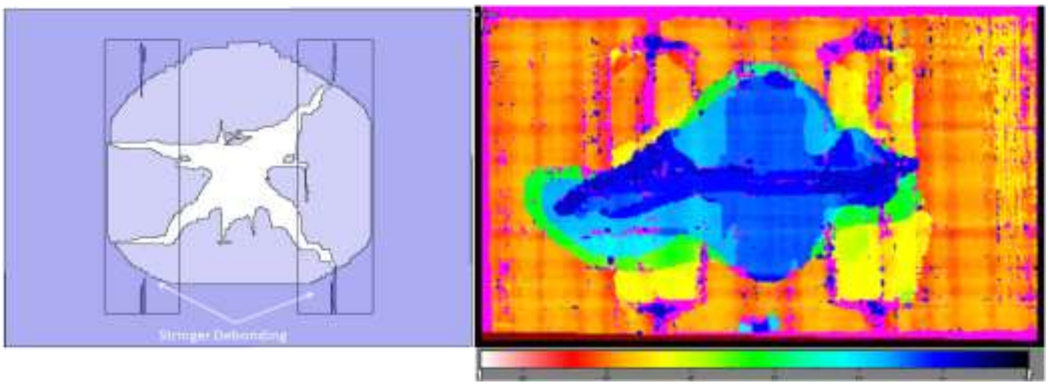


Figure 30: Correlation between delamination simulation results (left) and NDT inspection (right) after Ice impact Shedding

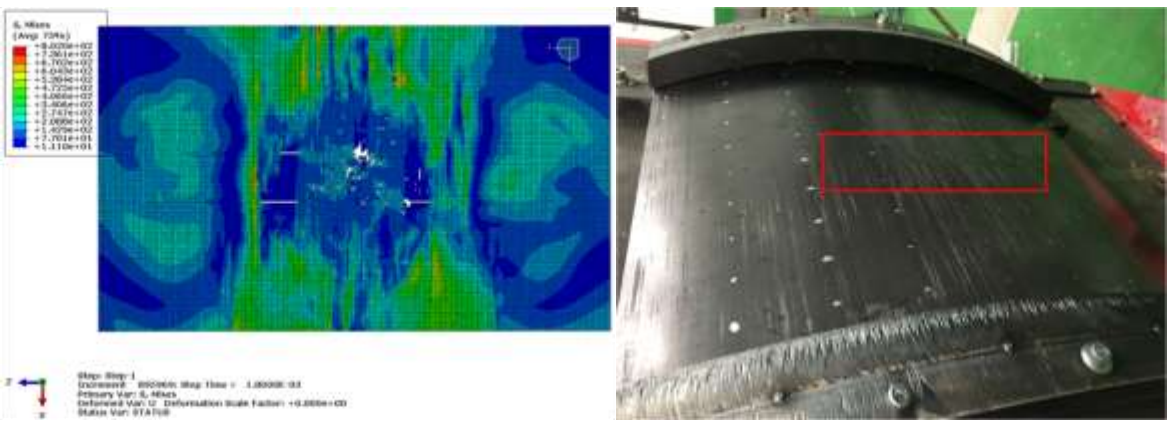


Figure 31: Correlation between intralaminar failure on impacted specimen surface simulation results (left) and visual inspection (right) after Ice impact Shedding

The displacement value of the inner surface centre of the stiffened panel was tracked with the high speed video and the correlation between experimental and simulation displacement was quite good also.

The conclusions are that impact results are accurately correlated with the same material model that correlates at low energy impact (drop weight tower) and also at medium energy impact (Ice Shedding impact). The model is therefore validated with experimental tests at component level and can be used for predicting other impact scenarios with the same material.

3.6. Demonstration of LOWFLIP technologies on selected demonstrators

After the installation of the full-scale automated production cells in WP7, three demonstrator parts have been realized with the new process and tooling approaches.

In case of the large parts, the truck front wall has been produced with the new tapelaying process. The different layer orientations were realized by rotating the tool. In this way, a quasiisotropic layup was realized, which shall meet the requirements on the mechanical performance of the part. The tapelaying process proved to be very efficient with regards to its layup rate and can be further optimized by improving the programmed robot paths. Especially the interaction of grippers and compaction rollers proved to be a complex issue which requires a smart vector-based off-line programming solution.

Figure 32. Manufactured demonstrator parts in LOWFLIP. Left: Truck front wall, Middle: Automotive cross-beam, Right: Aeronautic tail cone section

The plies could be deposited on the mould with high accuracy. Especially along single-curved mould sections, no gaps occurred in between the plies. Along double-curved surfaces, the optimization of the robot positions is crucial in order to realize high quality laminates. Within the project, a part could be realized within 2,5 working days with a ready-to-use robot program. Since these were the very first prototypes manufactured with the system, a large potential towards faster production cycles is given, e.g. by adding an automated material cutting solution to the system, which has been done by manually in the project. A drawback of the production system is – as it is also the case for other AFP/ATL processes – that corner sections cannot be produced automatically if the radius becomes too small. This could be optimized by using additional end-effectors on the compaction unit, which are capable of draping the material into sections with extreme curvature.

In case of the 3D-draping cell, the automotive part could be realised fully automated within a cycle time of 40 minutes, which can be further reduced with the available tools to 20 minutes (1 mould) or even 10 minutes with two moulds, which is lower than the targeted cycle time of 30 minutes/part to produce around 10,000 parts per year. The pick & place unit was able to lift up both carbon fiber prepreg stacks as well as the integrated sandwich core and place them accurately on the mould. Both membrane solutions – the elastic membrane for preforming the material and the 3D membrane with integrated heating – showed their capability of realizing complex shaped parts within a flexible production environment.

Figure 33. Full-scale tapelaying production cell running on test part production (truck front wall)

Figure 34. Automated positioning of the sandwich foam core for the automotive demonstrator.

4. Potential impact and main dissemination activities and exploitation of results

LOWFLIP PERSPECTIVES

- A **new process concept** for the composites manufacturing sector
- A **new raw material** (snap-cure semipreg) to be available on a commercial basis
- A **significant reduction** of the **investment costs** compared to current SoA technologies like ATL, AFP and RTM
- A **significant reduction** of the **energy consumption** during manufacturing
- Lightening of parts and thus **reduction of energy consumption** of vehicles and aircraft
- A technology transfer process to automotive, truck and aerospace sectors

According to the LOWFLIP perspectives initially set up at the beginning of the project effective project results have been reached. Besides the developed technologies, market analysis still has to be carried out in order to obtain detailed quantitative outcome.

4.1. Main exploitation results

Prepreg materials based on the novel snap-cure resin system SCE79 will be commercially available from SGL. These materials include the ones utilized in the LOWFLIP project (unidirectional prepregs and biaxial semi-pregs) but resin system SCE79 can generally be used in combination with very different customary fibrous reinforcement materials depending on the needs of a specific application. For example, higher or lower fiber areal weights, different fiber orientations and other types of fibers like glass fibers may be employed. Additionally, other snap-cure prepregs are now available from SGL which have been tailored for curing at higher temperatures providing even shorter cure cycles (e.g. < 3 min at temperatures ≥ 150 °C).

The developed production systems allow for the automated production of CFRP components for both small/complex geometries as well as large parts. Due to their flexibility, they can be used for different applications. Compared to state-of-the-art solutions, the production cells require significantly less investment costs, as no autoclave or presses are needed for the consolidation of the material. In case of the advanced ply placement process, investment costs could be reduced by separating the material feeding and consolidation system. Thus, there is now need for a complex, integrated tapelaying end-effector. The solutions were built up on an industrial scale and can be transferred to the market, allowing for the automated production of lightweight structures not only by OEMS, but also by small and medium-sized companies.

4.2. Potential impact

The newly developed automated process for the production of lightweight structural parts in combination with a novel material system has great potential for introducing CFRP parts into different industrial sectors. The production cells offer high economic advantages compared to state-of-the-art manufacturing technologies, as they can strongly reduce the required investment costs, thus also enabling the introduction of automated composite production in small and medium-sized companies. By combining the mechanical advantages of CFRP materials with their ability to form complex shapes, it is a highly interesting material for not only the aeronautic sector, but also for the truck and automotive industry – especially with regards to the aim of strongly reducing CO_2 emissions by lowering the weight and improving the aerodynamic behaviour of vehicles. However, the introduction of CFRP in those cost-competitive branches require the ability to automatically produce parts with low-invest, which can now be achieved with the developed LOWFLIP technologies.

4.3. Main dissemination results, technology and knowledge transfer

A major goal of LOWFLIP is the transfer of knowledge to further exploit the results of the project after the project end.

First, the foreground developed should be documented in a way that enables both the partners and a public audience to benefit from it.

Second, the developed technologies should be transferred to the industry to generate a benefit for potential end users and thus to create a maximum impact with regards to the lightweight production technologies with CFRP materials.

To reach both objectives, different actions were taken in the course of the project. For the transfer of knowledge into a scientific community, both written documents and oral presentations were created by the partners.

The results achieved were also presented at several international events to reach a wider community. This included a press release in JEC Composites magazine to announce the launch of the project, the creation of a LOWFLIP website (www.lowflip.eu) and the presentation at the JEC World exhibition in Paris, France in 2015 and 2016.

In total, **9 scientific publications and 30 dissemination activities** have been listed, covering a wide range from written publications, presentations and live shows. The total size of the audience addressed by these activities is in the range of **more than 10.000 people**. Figure 35 lists an excerpt of the list of dissemination activities. It can be said that a huge effort has been done by all partners to disseminate the project activities during the project and – even more importantly – that a lot of activities are planned after the project end, which shows the significance of the obtained results.

22	Video	Ayming, All	Final LOWFLIP video	Sept 2016	http://www.lowflip.eu	Scientific community and industry			All
23	Exhibition	Fill, IFB	JEC Augsburg award on tape laying cell	21-23 Sept 2016	JEC Augsburg: Experience Composites	Scientific community and industry		500	All
24	oral presentation to a conference	MECAS	Presentation of Lowflip simulation activities	September 29-30 2016	VPS User Forum 2016 held in Brasy, Czech republic	Scientific community and industry			All
25	exhibition	Fill, Tecnalia	Presentation of pick and place cell (gripper+ robot and Alpex mould) at Fill booth	19-26th October 2016	K exhibition in Dusseldorf	Industry		500	All
26	Article in newsletter	Fill, Tecnalia	Presentation of pick and place cell gripper	October 2016	WITTENSTEIN (supplier of gripper engines) newsletter	Industry			All
27	exhibition	Fill	Presentation of pick and place cell (gripper) at Wittenstein booth	22-24 Nov 2016	SPS IPC Drives exhibition in Nuremberg	Industry		400	All
28	oral presentation to a workshop	Fill, Tecnalia	Flexible automation as a key enabling technology to produce multimaterial structural parts	8th November 2016	Advanced Multimaterial Structures in Automotive workshop in Bilbao	Scientific community and industry		100	Spain

Figure 35. Excerpt from the list of dissemination activities (D10.3)

A key issue towards a successful exploitation of the results was an early collection of possible exploitable results of the partners during the first general meeting at Carbures in April 2014. The list of exploitable results was continuously extended by the partners in the following meetings.

The partners also helped to disseminate the project activities by referencing e.g. LOWFLIP videos on their own Youtube-Portal or within their Linkedin-Group. Social media has therefore been addressed additionally to easily spread the results of the project even to a larger public.

In order to exploit the results further after the project end, further use, optimization and research on the developed technologies is a key element to bridge the gap between research/innovation activities and industrial use. Therefore, it has been decided by the consortium to transfer the developed prototype production cells to the involved research institutes, so that further work can be performed in future collaborations. The production cell for small & complex parts will be transferred to Tecnalia, while the production cell for large parts will be delivered to USTUTT after the project end.

Future collaborations in other research projects have been strongly encouraged by the project management and first discussions already started during the project lifetime.

In case of the developed prepreg material, further development and sale of the product is planned. It is obvious that research partners mainly aim at using the developed results in new research projects, while industrial partners plan to sell the developed products in their individual sector. The exploitation claims, which were gathered at the beginning of the project, will help the partners to identify their relevant exploitable results and also to find potential partners for future collaboration in the same field of interest.